Workshop for Applied Nuclear Data Activities (WANDA)
United States Department of Energy, Virtual conference
Plenary Session

NUCLEAR DATA NEEDS FOR HUMAN SPACE RADIATION SHIELDING

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Outline

INTRODUCTION

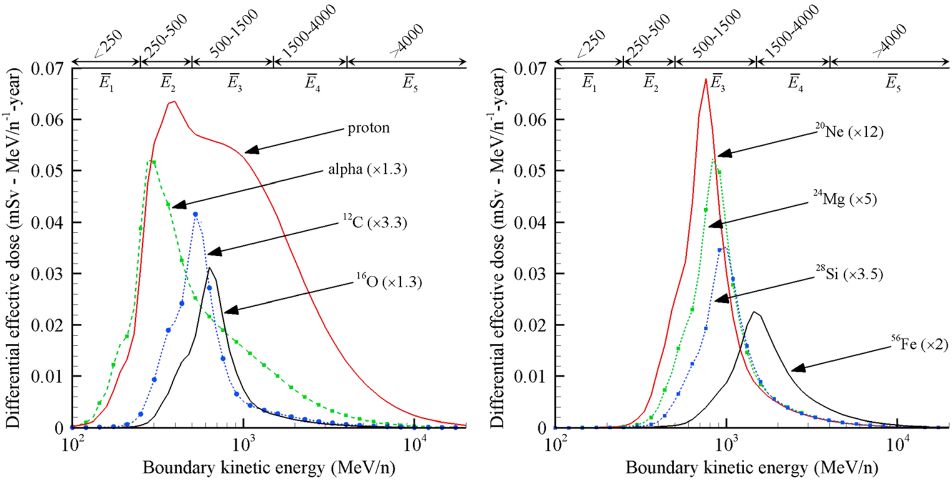
- Sensitivity studies have been performed to quantify relative importance of specific ions and energies in the galactic cosmic ray (GCR) spectrum to exposure behind shielding and tissue
  Slaba & Blattnig, Space Weather 12, 217, 2014

- 90% effective dose contributed from GCR energies $>$ 250 MeV/n
  = Upper energy limit of Advanced Composition Explorer / Cosmic Ray Isotope Spectrometer (ACE/CRIS) satellite
  = Most of the GCR data

- Higher energy data needed
  - Alpha Magnetic Spectrometer (AMS) measurements important

- Heavier GCR nuclei ($>$ ^{16}O) contribute less

Effective dose contributions as a function of energy



Slaba & Blattnig, Space Weather 12, 217, 2014

- Effective dose contributions
  - Medium GCR energy (250 MeV/n – 3 GeV/n)
  - Light GCR nuclei $< {}^{16}$O
  - Fe not very important
- MSLRAD spectra
  - All GCR energies (higher)
  - All GCR nuclei (heavier)

INTRODUCTION

- Light ions are isotopes of Hydrogen & Helium
  - proton = ^{1}H, deuteron = ^{2}H, triton = ^{3}H, helion = ^{3}He, alpha = ^{4}He
- Light ions & neutrons dominate dose equivalent for realistic shield thicknesses ($\geq$ 20 g/cm^{2}) Norbury & Slaba, Life Sci. Space Res. 3, 90, 2014
- Light ions & neutrons are scattered at large angles
  - Require 3-dimensional transport & nuclear physics
  - 3DHZETRN & double differential cross sections

Introduction - Discrepancies

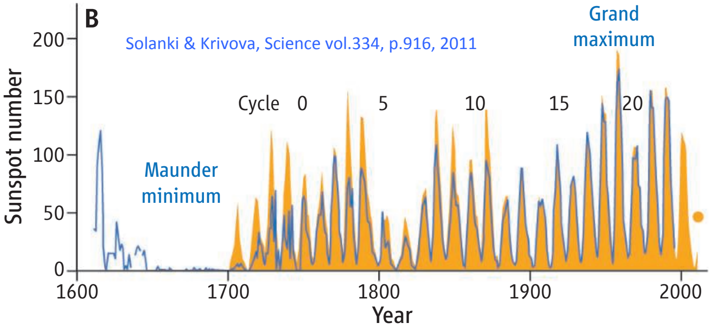
- Transport codes show largest differences for light ions
  - GEANT, FLUKA, MCNP, PHITS, HZETRN, SHIELD(Russia)
  - Due to uncertain light ion nuclear physics models (coalescence & heavy ion breakup) and lack of experimental data
- Thick target measurements show significant discrepancies compared to transport codes (MCNP, PHITS) for light ions
- MSLRAD light ion flux measurements highlight need for improved nuclear interaction models
  - Light ion model results show significant discrepancies over MSLRAD energy range
  - Model errors due to inaccurate light ion nuclear physics models
  - Discrepancies don't contribute significantly to dose equivalent, but improvements would yield better agreement with MSLRAD

INTRODUCTION

- Light ion cross sections
  - Largest physics uncertainty in space radiation
- Light ion cross section measurements
  - Largest gap in cross section database
    Norbury et al., Rad. Meas. 47, 315, 2012
- Light ion cross section measurements needed
  - To improve inaccurate light ion nuclear physics models

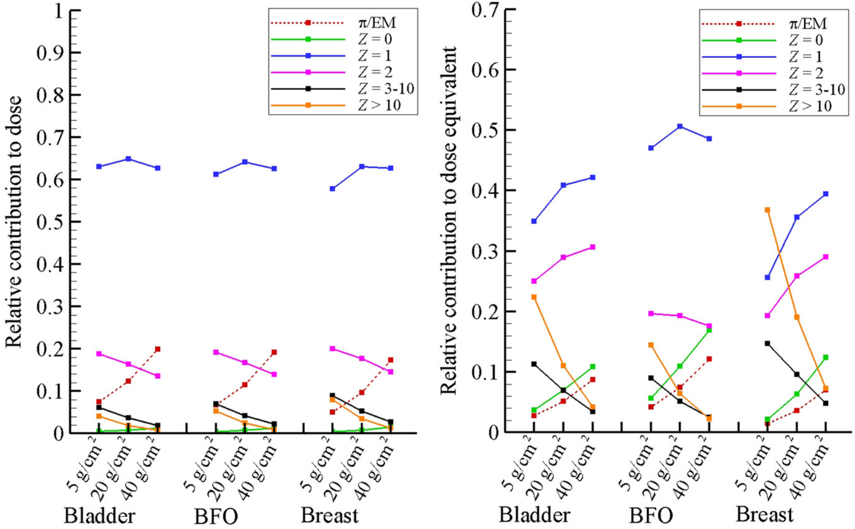
Percent contribution to blood forming organ (BFO) dose equivalent by charge group

- The space age has coincided with the *Solar Modern Maximum*, which is a century long peak in solar activity



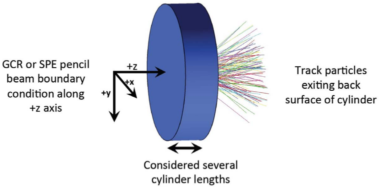
Walker, Townsend, Norbury, Adv. Space Res. 51, 1792, 2013

Percent contribution to organ dose equivalent by charge group



Slaba, Blattnig, Norbury, Rusek, La Tessa, Life Sci. Space Res. 8, 52, 2018

Transport code comparisons



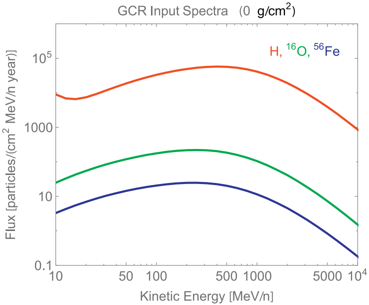
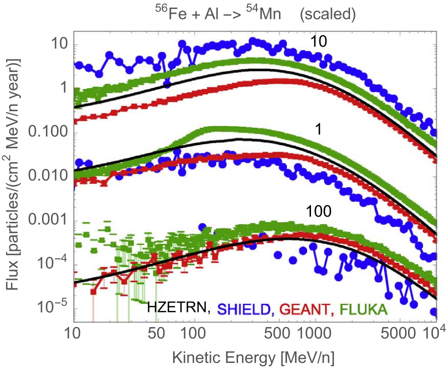
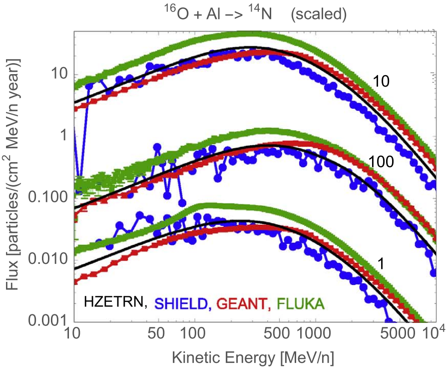


Fig. 2. GCR minimum spectra.

Norbury, Slaba, Sobolovsky, Reddell, Life Sci. Space Res. 14, 64, 2017

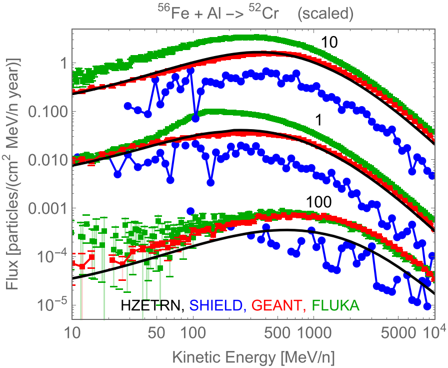
Transport code comparisons

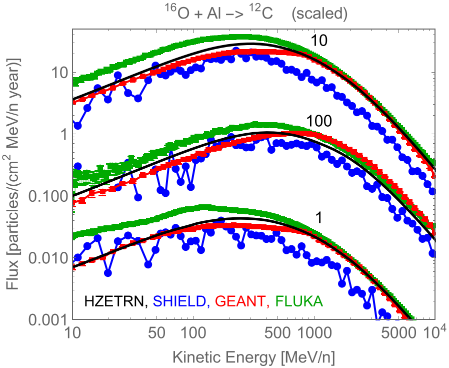




Norbury, Slaba, Sobolovsky, Reddell, Life Sci. Space Res. 14, 64, 2017

^{2}H, np *production discrepancies*



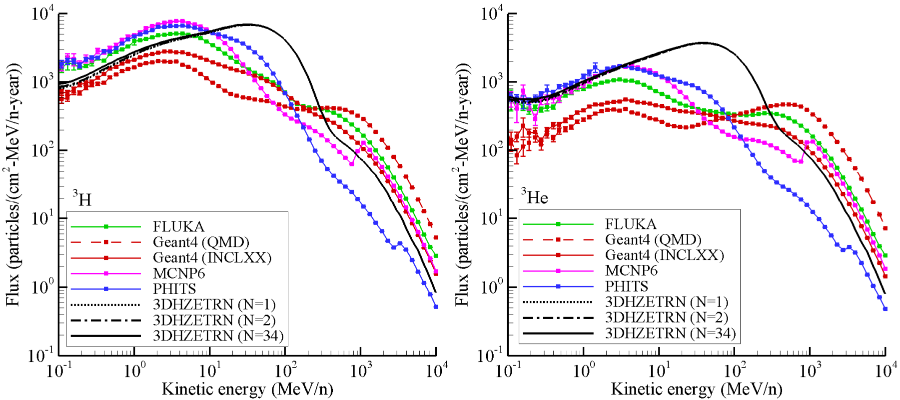


Norbury, Slaba, Sobolovsky, Reddell, Life Sci. Space Res. 14, 64, 2017

^{4}He, 2n2p *production discrepancies*

Transport code comparisons

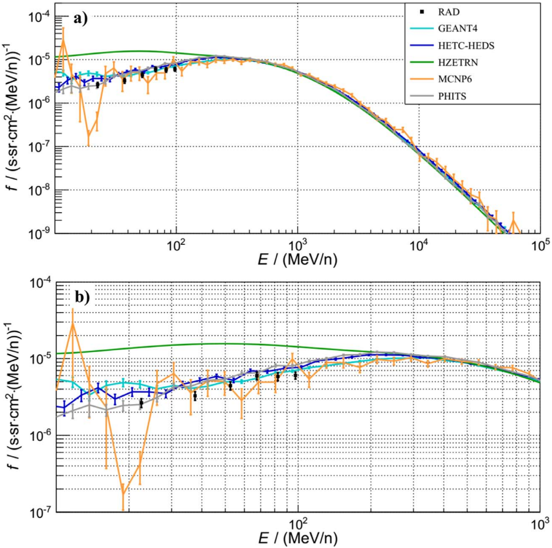
^{3}H and ^{3}He flux behind 60 g/cm^2 Al shield for GCR minimum spectrum - Thick targets



Slaba et al., Life Sci. Space Res. 12, 1, 2017

Significant discrepancies

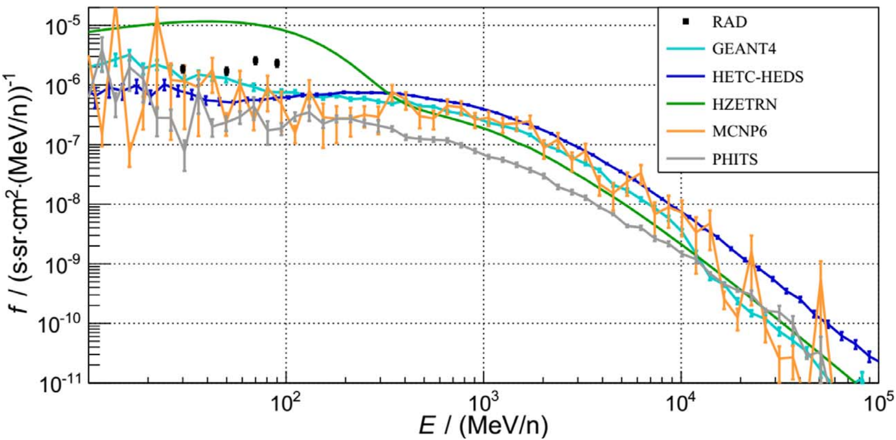
MSLRAD COMPARISONS ^{4}He



Matthia et al., Life Sci. Space Res. 14, 18, 2017

Low energy discrepancies

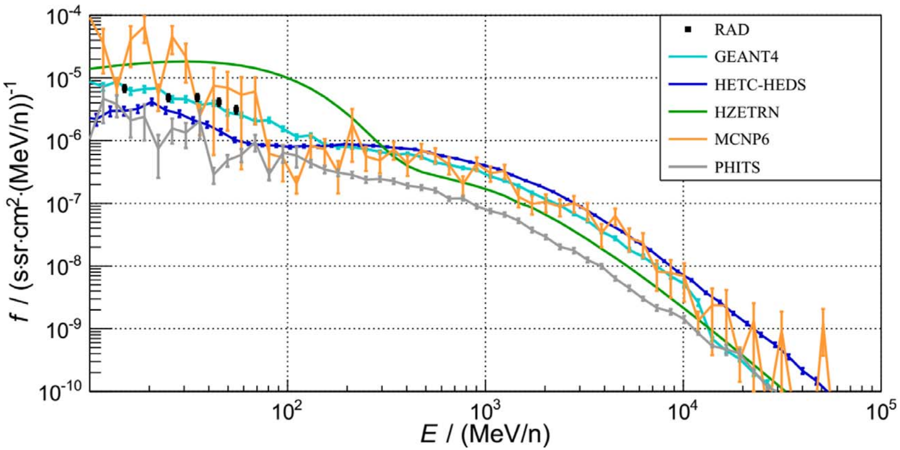
MSLRAD COMPARISONS ^{3}He



Matthia et al., Life Sci. Space Res. 14, 18, 2017

Significant discrepancies

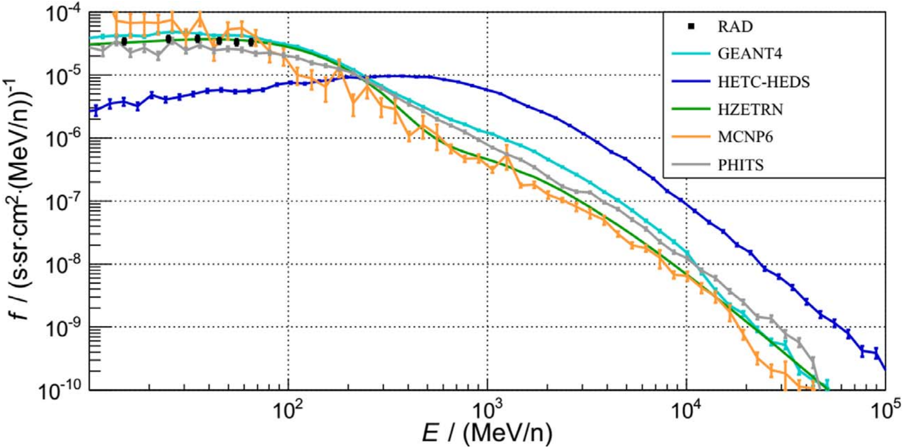
MSLRAD COMPARISONS ^{3}H



Matthia et al., Life Sci. Space Res. 14, 18, 2017

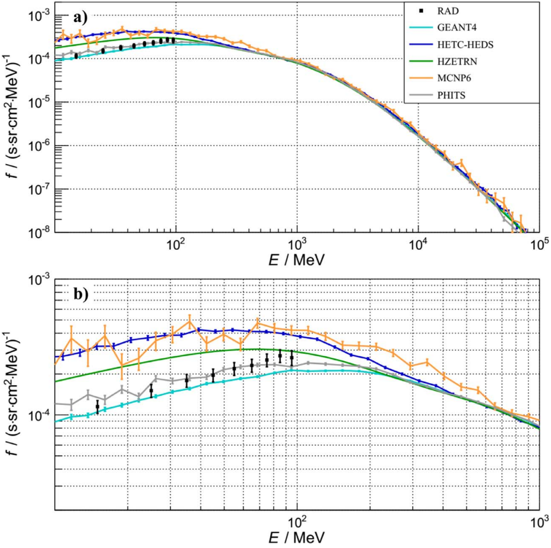
Significant discrepancies

MSLRAD COMPARISONS ^{2}H



Matthia et al., Life Sci. Space Res. 14, 18, 2017

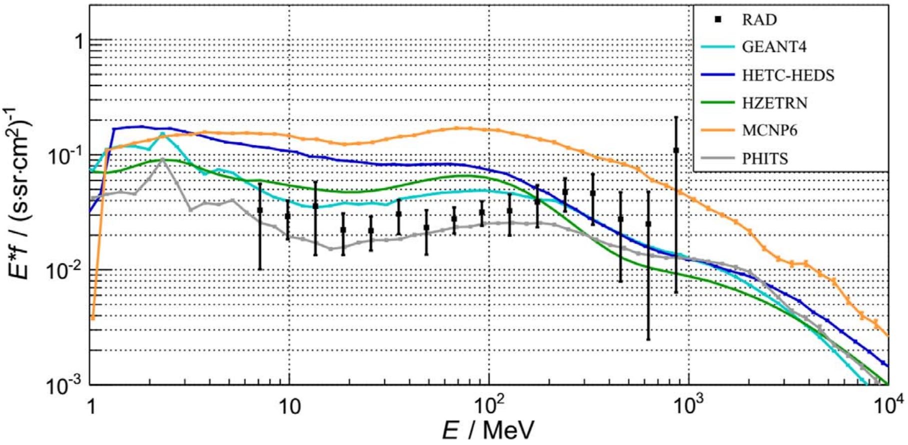
Significant discrepancies



Matthia et al., Life Sci. Space Res. 14, 18, 2017

Low energy discrepancies

MSLRAD COMPARISONS NEUTRONS



Matthia et al., Life Sci. Space Res. 14, 18, 2017

Significant discrepancies

SUMMARY

KE = kinetic energy, ED = effective dose, d = deuteron, t = triton, h = helion, p = proton, n = neutron, DD = double differential

Low Fragment KE $<$ 100 MeV/n

MSLRAD region; Small contribution to ED

- Light ion (d,t,h) fragments - nucleon (p,n) induced target frag.
  - Because many more protons (p) in GCR than heavier projectiles
    - neutrons (n) copiously produced as target thickness increases
- DD cross sections needed
  - Because low energy fragments scattered at large angles

High Fragment KE $>$ 3 GeV/n

Small contribution to ED

- Light ion fragments (d,t,h) come from heavier projectile breakup
  - High energy fragments scattered mainly at forward angles
    - seen in DD plots: 0° DD cross sections $>>$ 145° DD cross sections
  - DD cross sections not urgently needed for transport
    - but do provide best validation of nuclear models

Intermediate 100 MeV/n $<$ KE $<$ 3 GeV/n

Large contribution to ED

- Mixture of both above
- DD cross sections needed for transport

Cross section measurement database

Galactic Cosmic Rays (GCR)

- Protons $\rightarrow$ Fe nuclei $\sim$ 100 MeV/n $-$ 50 GeV/n
- Peaks: H, He, C, O, Si, Fe   Z = 1, 2, 6, 8, 14, 26

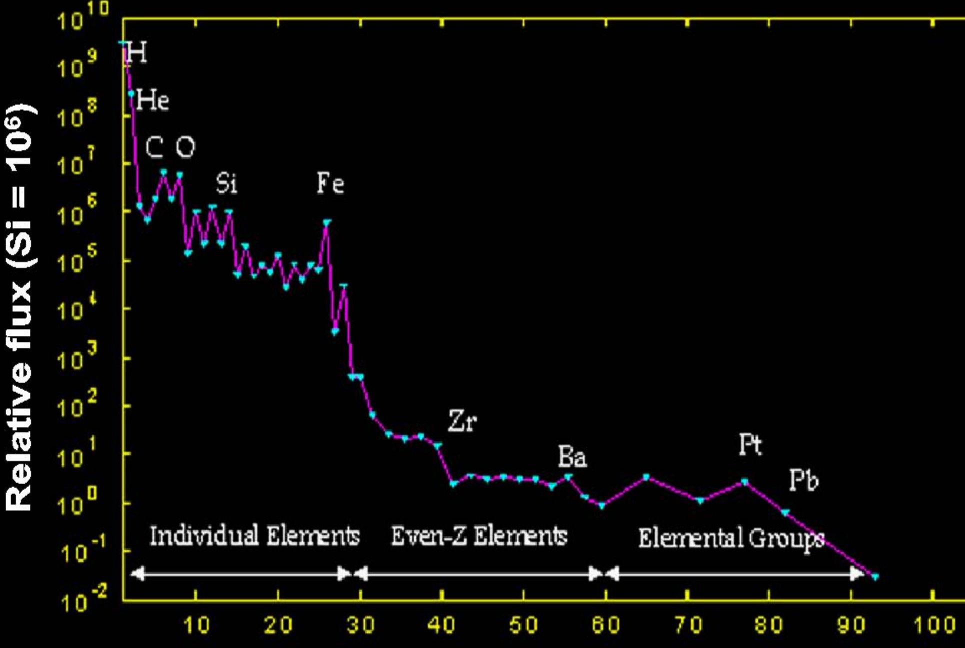
- NUCDAT (50,000 entries)

Norbury et al., Radiation Measurements 47, 315, 2012.
Health Physics 103, 640, 2013.
Journal of Physics (conf. ser.) 381, 012117, 2013.
Frontiers in Physics 8:565954, 2020.

"NASA has not made an adequate effort to collect, catalogue and categorize existing experimental data obtained by the worldwide heavy ion research community and make it available in appropriate form to the shielding engineering community."

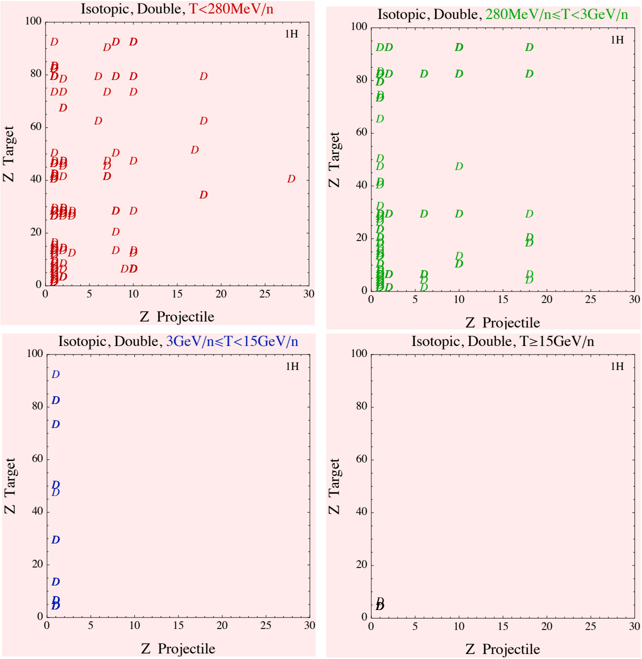
National Research Council of the National Academy of Sciences, *Managing space radiation risk in the new era of space exploration*, The National Academies Press, Washington D.C. (2008). Finding 5-6. Experimental data for designers.

Energy = 2 GeV/n, normalized to silicon = 10^6



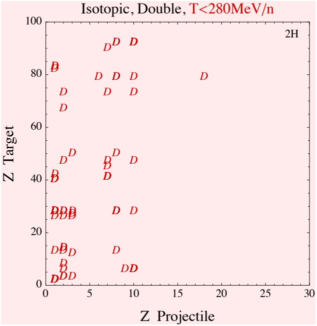
Cross section measurement database

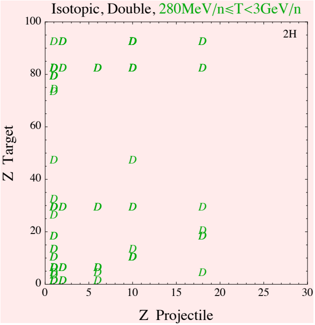
- NUCDAT database: $\sim$ 50,000 entries
  - ZP, AP, TP, ZT, AT, ZF, AF
  - Cross section type
    - total, differential, charge changing, elemental, isotopic, ...
  - Double differential most useful
  - Bibliography
  - Other
  - No actual data - only that data exists
- Energy regions:
  - Below pion threshold: $\mathrm{T} < 280\,\mathrm{MeV/n}$
  - Low: 280 MeV/n $\leq$ T $<$ 3 GeV/n
  - Medium: $3\,\mathrm{GeV/n} \leq \mathrm{T} < 15\,\mathrm{GeV/n}$
  - High: $\mathrm{T} \geq 15\,\mathrm{GeV/n}$
- Fragments:
  - Light (H, He) - TODAY ONLY
  - Medium-Light ($\mathrm{Z_F} = 3 - 9$) ($\mathrm{Li} - \mathrm{F}$)
  - Medium ($\mathrm{Z_F} = 10 - 19$) ($\mathrm{Ne} - \mathrm{K}$)
  - Heavy ($\mathrm{Z_F} = 20 - 30$) ($\mathrm{Ca} - \mathrm{Zn}$)
  - Very Heavy ($\mathrm{Z_F} > 30$)



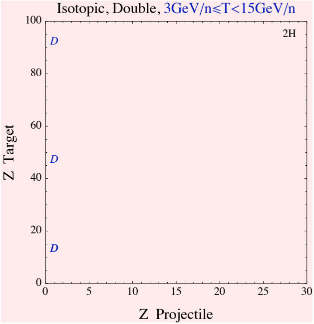
$^{1}\mathrm{H}\ \frac{d^2\sigma}{dE d\Omega}$

GCR peaks Z = 1, 2, 6, 8, 14, 26

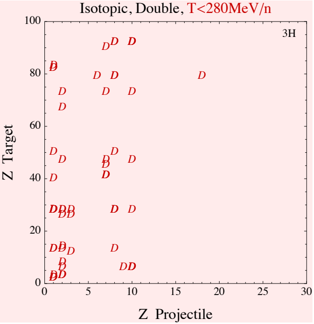


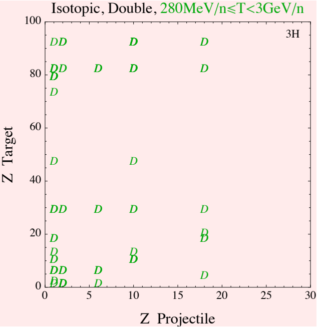


$$^{2}\mathrm{H}\ \frac{d^2\sigma}{dE\,d\Omega}$$

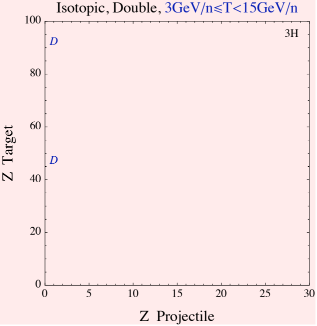


GCR peaks Z = 1, 2, 6, 8, 14, 26

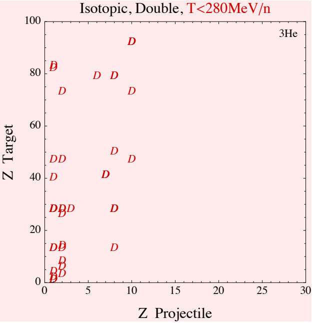


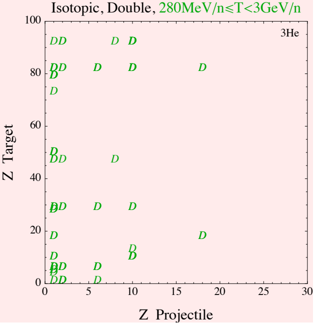


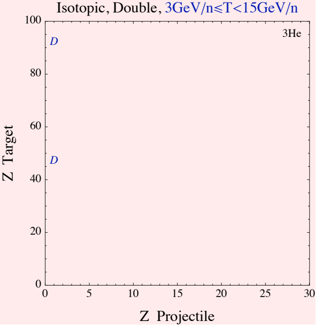
$^{3}\mathrm{H}\ \dfrac{d^2\sigma}{dEd\Omega}$



GCR peaks Z = 1, 2, 6, 8, 14, 26

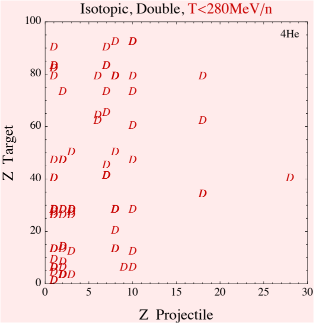


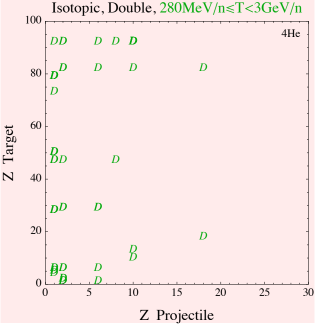




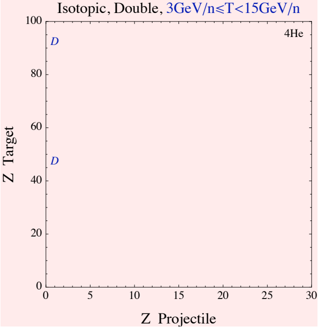
$^3\mathrm{He}$ $\dfrac{d^2\sigma}{dEd\Omega}$

GCR peaks Z = 1, 2, 6, 8, 14, 26





$$ {}^4\mathrm{He} \quad \frac{d^2\sigma}{dE\,d\Omega} $$



GCR peaks Z = 1, 2, 6, 8, 14, 26

Additional measurements:

- M. Beach, L. Heilbronn et al. (unpublished)
  NASA Space Radiation Lab at Brookhaven National Lab
  ^{16}O (300 MeV/n), ^{56}Fe (600 MeV/n) + Al, C, $CH_4 \rightarrow {}^{1,2,3}$H, ^{3,4}He
  - data tables

- Toppi et al. (FIRST), Phys. Rev. C vol. 93, p. 064601, 2016
  GSI
  ^{12}C (400 MeV/n) + Au $\rightarrow {}^{1,2,3}$H, ^{3,4}He, ^{6,7}Li, ^{7,9,10}Be, ^{10,11}B
  - data tables published

Cross section measurement database - Details

Details of light ion production double differential cross sections:

Proj.	KE MeV/n	Target	Fragment	Author	Note	Comments
^{1}H	100 - 200	Ni,Mo,Au	^{1}H	Richter 1982	0^{o} - 140^{o}	
^{1}H	500	^{4}He,Ni,Ta	^{1}H	Roy 1981	> 65^{o}	
^{1}H	600	C, Al, Au,	$^{1,2,3}H$, $^{3,4}He$	Alard 1975	> 30^{o}	
^{1}H	660	B,Ni,Sn,Sm	$^{3,4}He$	Bogatin 1976	90^{o}	
^{1}H	800	$^{1,2}H$,C,Ca,Pb	^{1}H	McGill 1984	> 5^{o}	
^{1}H	800	KCl	^{1}H	Nagamiya 1981	> 10^{o}	
^{1}H	1050, 2100	Au	^{1}H	Geaga 1980	2.5^{o}, 180^{o}	
^{2}H	1050	C	^{1}H	Anderson 1983	0^{o}	Fig.7
^{2}H	2100	U	^{4}He	Gossett 1977	90^{o}	Fig.6* (* only lines)

Cross section measurement database - Details

Proj.	KE MeV/n	Target	Fragment	Author	Note	Comments
^{3}He	33 (exception)	Ho	^{1,2,3}H	Motobayashi 1984		
^{3}He	67 (exception)	Ag	^{1}H	Zhu 1991	> 33^{o}	
^{4}He	27 (exception)	Ho	^{1}H	Shibata 1985	15^{o} - 150^{o}	
^{4}He	180	Al, Ag, Ta	^{1,2,3}H, ^{3,4}He	Doering 1978	> 60^{o}	
^{4}He	383	C	^{1,2,3}H, ^{3}He	Anderson LBL-6769	0^{o}	Fig.24
^{4}He	250	U	^{1,2,3}H, ^{3,4}He	Gossett 1977	> 20^{o}	Fig.10*
^{4}He	400	U	^{1}H	Westfall 1976	> 30^{o}	Fig.3
^{4}He	400	U	^{1,2,3}H, ^{3,4}He	Gossett 1977	> 20^{o}	Fig.10*
^{4}He	400	U	^{1}H, Li, ^{7,9,10}Be, B	Gossett 1977	> 30^{o}	Fig.18*,26
^{4}He	400	C	^{1}H	Anderson 1983	0^{o}	Fig.23 xF
^{4}He	1010	H	^{3}He	Bizard 1977	1 - 10^{o}	
^{4}He	1050	^{2}H, ^{3,4}He	^{4}He	Banaigs 1987	< 15^{o}	Elastic & inelastic
^{4}He	1050	C	^{1}H	Anderson 1983	0^{o}	Fig.7
^{4}He	1050	C	^{4}He	Anderson 1983	pT	Fig.10
^{4}He	1050	C	^{1,2,3}H, ^{3}He	Anderson 1983	0^{o}	Fig.3
^{4}He	1050, 2100	C	^{1}H	Anderson 1983	0^{o}	Fig.23 xF
^{4}He	1050, 2100	C	^{1,2,3}H, ^{3}He	Anderson LBL-6769	0^{o}	Fig.25,26
^{4}He	1050, 2100	C	^{1}H	Anderson 1983	0^{o}	Fig.21
^{4}He	2100	C	^{1}H	Anderson 1983	pT	Fig.8
^{4}He	2100	H, C, Cu, Pb	^{4}He	Anderson 1983	pT	Fig.10
^{4}He	2100	C	^{1}H	Anderson LBL-6769	pT	Fig.28
^{4}He	2100	U	^{4}He	Gossett 1977	90^{o}	Fig.6*

Cross section measurement database - Details

Proj.	KE MeV/n	Target	Fragment	Author	Note	Comments
^{12}C	35 (exception)	Au	$^{1,2,3}H$, $^{3,4,6}He$	Westfall 1984	> 40°	
^{12}C	800	C, KCl	$^{1,2,3}H$, $^{3,4}He$	Nagamiya 1981	> 10°	Lemaire supplement
^{12}C	1050	C	$^{1,2,3}H$, $^{3,4,6,8}He$	Anderson 1983	< 10°	Fig.4,7,10
^{12}C	1050, 2100	Au	^{1}H	Geaga 1980	2.5°, 180°	
^{12}C	2100	U	^{4}He	Gossett 1977	90°	Fig.6*
^{16}O	52, 100, 147	Ni, Sn	$^{1,2,3}H$, $^{3,4}He$	Auble 1983	> 6°	
^{16}O	300	Al	$^{1,2,3}H$, $^{3,4}He$	Beach 2016	0° - 90°	Analysis in progress
^{16}O	2100	U	^{4}He	Gossett 1977	90°	Fig.6*
^{20}Ne	100, 156		$^{1,2}H$, ^{4}He	Westfall 1982	> 50°	
^{20}Ne	250, 400	U	$^{1,2,3}H$, $^{3,4}He$	Gutbrod 1976	30° - 150°	Same as Gosset ???
^{20}Ne	250, 400, 2100	U	^{1}H	Westfall 1976	> 30°	Fig.3
^{20}Ne	250, 400, 2100	U	$^{1,2,3}H^{3,4}HeLi^{7,9,10}BeBCNO$	Gossett 1977	> 20°	
^{20}Ne	250, 400, 2100	Al	$^{1,2,3}H$, $^{3,4}He$	Gossett 1977	> 20°	Fig.7*,8*,9*,11*,26,29
^{20}Ne	400, 2100	U	$^{1,2,3}H$, $^{3,4}He$	Gossett 1978	> 30°	Fig.1,2,3,4,5
^{20}Ne	800	NaF, Pb	^{1}H	Gossett 1978		Fig.9,11 Rapidity
^{20}Ne	2100	U	^{4}He	Gossett 1977	90°	Fig.6*
^{20}Ne	2100	U	$^{3,4,6}He$, $^{6,7,8}Li$, $^{7,9,10}Be$	Gossett 1977	90°	Fig.5
^{40}Ar	1050, 2100	Au	^{1}H	Geaga 1980	2.5°, 180°	
^{40}Ar	800	C, KCl	$^{1,2,3}H$, $^{3,4}He$	Nagamiya 1981	> 10°	Lemaire supplement
^{40}Ar	1800	Be, Cu	$^{1,2,3}H$	Gossett 1978	5°, 15°	Fig.6,7,8
^{40}Ar	1800	Be, Cu	$^{1,2,3}H$	Gazzaly 1978	5 ° - 15°	
^{56}Fe	400	CH_2, C, Al	$^{1,2,3}H$, $^{3,4}He$	Beach 2017	0° - 90°	Analysis in progress

Cross section measurement recommendations

Final recommended reactions

Fe,Si,O,He + H,C,Al,Fe $\rightarrow$ ^{1,2,3}H, ^{3,4}He (isotopic dd & total reaction σ)

1.5 GeV/n, 800 MeV/n, 400 MeV/n

dd = double differential

- Projectile priorities: 1) Fe 2) Si 3) O 4) He
- Targets: H, C, Al (all equal priority), Fe (lesser priority)
  – CH_2 target easier than H target - get H σ from CH_2 target by subtracting C σ
- Energy priorities: Span range of energies available above 300 MeV/n, with more emphasis on higher energies
  1) 1.5 GeV/n 2) 800 MeV/n 3) 400 MeV/n
  – based on contribution to effective dose & lack of high energy data
  – need all 3 energies to properly test models
  – Fe gap greater at higher energy
- BUT difficult to separate isotopes at higher energy, with present detectors
- Expect physics to change more as a function of projectile, rather than energy
  – varying projectiles more important than varying energy
- Have not discussed neutron cross section gaps
  – preliminary analysis reveals no data above 1 GeV/n

Summary & Conclusions

- Light ions & neutrons make large contributions to dose equivalent
- Light ion cross sections
  - Largest physics uncertainty in space radiation
  - Large gap in measurement database
- Final recommended reactions at NSRL
  - Fe,Si,O,He + H,C,Al,Fe $\rightarrow$ ^{1,2,3}H, ^{3,4}He
  - Isotopic dd & total reaction σ
  - 1.5 GeV/n, 800 MeV/n, 400 MeV/n
- Neutron cross sections $\sim$ Nothing above 1 GeV/n

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THE END